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SPECIAL ISSUE

The use of autonomous vehicles for spatially measuring mean velocity profiles in rivers and estuaries

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Abstract Autonomous vehicles (AVs) are commonly used in oceanic and more recently estuarine and riverine environments because they are small, versatile, efficient, moving platforms equipped with a suite of instruments for measuring environmental conditions. However, moving vessel observations, particularly those associated with Acoustic Doppler Current Profiler (ADCP) measurements, can be problematic owing to instrument noise, flow fluctuations, and spatial variability. A range of ADCPs manufactured by different companies were integrated on to an Unmanned Surface Vehicle (USV), an Unmanned Underwater Vehicle (UUV), and some additional stationary platforms and were deployed in a number of natural riverine and estuarine environments to evaluate the quality of the velocity profile over the depth, minimum averaging time interval requirements, and AV mission planning considerations. Measurements were obtained at fixed locations to eliminate any spatial variations in the mean flow characteristics. The USV has the unique capability to station-keep to within 1 m owing to its dual-propeller design, providing the best setup for spatially mapping velocity profiles. Single-propeller UUVs can perform a quasi-station-keeping (<10 m) operation, but are designed for traveling underwater at speeds >1 m/s. An appropriate averaging window, T_*, was determined using the Kalman Algorithm with a Kalman gain equal to 1%. T_* was found to be independent of depth, flow velocity, and environment. There was no correlation ($R^2 = 0.18$) for T_* between flow magnitude and direction. Results from all measurements had a similar T_* of approximately 3 min. Based on this, an averaging window of 4 min is conservatively suggested to obtain a statistically confident measure of the mean velocity profile.

Keywords Unmanned Surface Vehicle (USV) · Unmanned Underwater Vehicle (UUV) · Acoustic Doppler Current Profiler (ADCP) · Velocity profile · Riverine · Estuarine

1 Introduction

The versatility and flexibility of autonomous vehicles (AVs) provide a unique environmental survey platform. AVs are small in size, typically capable of being deployed and operated by one person, and are equipped with a sensor suite comparable to those generally mounted on larger sized vessels. The size and weight of sensors continue to decrease while vehicle functionality and capability continue to increase, providing scientists with a new set of tools to improve our understanding of various aquatic environments. In addition to shrinking the size of vehicle platforms and sensors, the associated cost of AVs are becoming more affordable, especially when the operating costs, such as vessel maintenance, personnel, and fuel are included. This affords the scientist with the ability to procure and deploy AVs in natural environments, allowing for greater spatial coverage, reducing the time necessary to complete data collection, and reducing logistical costs. AVs come in a variety of shapes and sizes resulting in different capabilities and limitations.

Standard aquatic AVs are equipped with a combination of positioning, depth, velocity, and water quality sensors. Since

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most AVs are continuously moving, issues of instrument noise, environmental noise (scales), and stationarity (if averaging is performed) must be considered. Instrument noise is assumed to be a random process. Therefore, statistical confidence of the mean is gained by obtaining a number of observations, which are then averaged. The greater the number of *independent* observations (N) collected, the higher the confidence in the mean [2]. However, there is a point of diminished returns, and determining this point (in time) is critical for designing an efficient sampling scheme. The number of observational points considered to be independent is given by

$$N = \frac{T}{t_{\mathrm{decorr}}} = \frac{n \cdot dt}{t_{\mathrm{decorr}}} \tag{1}$$

where t_{decorr} is the environmental decorrelation time, T is the total sampling duration, and $T = n \cdot dt$, where n is the total number of observations and dt is the instrument sampling rate. For random data (e.g. instrument noise) $t_{\mathrm{decorr}} = dt$, and each observational data point is considered independent regardless of sampling frequency ($N = n$). However, in nature there can be random processes that have statistically ensemble-defined temporal and spatial scales leading to longer decorrelation times. For example, if $t_{\mathrm{decorr}} = 10$ s, and an instrument samples for $T = 100$ s, the record will consist of $N = 10$ independent observations, or degrees of freedom, regardless of the instrument sample rate. If the observations are collected from a moving platform, spatial limitations are also required such that the mean and environmental scales (noise) are not evolving (stationarity) within the sampling duration required to obtain a statistically confident estimate of the mean. Therefore, the appropriate AV sampling scheme is dependent upon instrument noise, the environment, the vessel speed, and the observations of interest including the required statistical confidence. In order to ensure a true estimate of the mean velocity is obtained when evaluating an appropriate averaging window, and to eliminate errors due to spatial variability from moving-vessel measurements, only measurements obtained by the vessels at fixed locations are considered in this work.

Acoustic Doppler Current Profilers (ADCPs) were originally implemented by scientists on aquatic AVs to provide dead-reckoning navigation based on a Doppler Velocity Log (DVL) [7]. However, ADCPs have recently been used on AVs to measure features including coastal ocean flows [1,5,7,13,18], directional surface waves [12], and depth-averaged currents [6]. There is an increasing need for collecting environmental data with AVs in faster and more dynamic flows found in riverine and estuarine environments. Historically, in rivers, ADCPs have been mounted on moving vessels to measure discharges [10,15,16,22], but there is a growing interest in collecting ADCP measurements for describing mean velocity profiles over the depth. Sophisticated data analysis techniques have been developed which are able to resolve the *depth-averaged* tidal and non-tidal flow behavior from moving-vessel (noisy) ADCP measurements [20,21]; however, the focus here is to resolve *depth-varying* currents. Current profiles have been successfully measured using fixed ADCPs in oceanic and estuarine environments, where ADCPs were either downward looking from buoy moorings or from the hulls of moored ships, or upward looking from bottom mounts [11].

ADCP measurements are inherently noisy. The statistical behavior of ADCPs, as a function of averaging time, is provided by all manufacturers and their software. In general, the suggested manufacturer's averaging time for which to obtain a statistically confident result is relatively short ($<$30 s). However, these estimates are strictly based on random instrument noise. The errors associated with the environment and/or the platform are not considered in the manufacturer's estimate owing to the range of applications utilized by the end-user. For moving-vessel velocity transect measurements, Fong and Jones [7] suggest averaging over $O(100)$ m is necessary to remove short-time and -spatial scale variability of ADCP measurements, which corresponds to approximately 2 min of averaging. Gonzalez-Castro and Muste [9] theoretically described all of the potential errors when using an ADCP on a moving vessel platform. Field observations are ultimately required to determine environmental noise and errors created by the quasi-stationary floating platforms described herein. At present it is recommended that fixed vessels collect 7–11 min of stationary data in order to resolve the instrument and environmental noise associated with ADCP measurements in riverine environments [17]. However, the recommended averaging time is based on visual estimates of when the mean flow velocity becomes stable using data collected in only one environment and therefore requires further examination. In order to accurately capture mean flow characteristics, the relationship between ADCP flow measurements obtained with AVs in differing non-wavy environments and the ADCP operational parameters also need additional evaluation. This paper focuses on two different AVs (SeaRobotics USV-2600 Unmanned Surface Vehicle, and YSI/Oceanserver Iver2 Unmanned Underwater Vehicle) equipped with ADCPs that were deployed in a river and tidal inlet and collected measurements at fixed locations, with the primary objective of obtaining statistically confident depth-varying velocity profiles and determining the associated averaging window necessary to remove instrument and environmental noise, as discussed by Muste et al. [17]. Knowledge of the appropriate averaging window required to obtain a statistically confident measure of the mean velocity, determined by robust statistical techniques, allows users to maximize their AV mission planning to optimize time and spatial resolution.

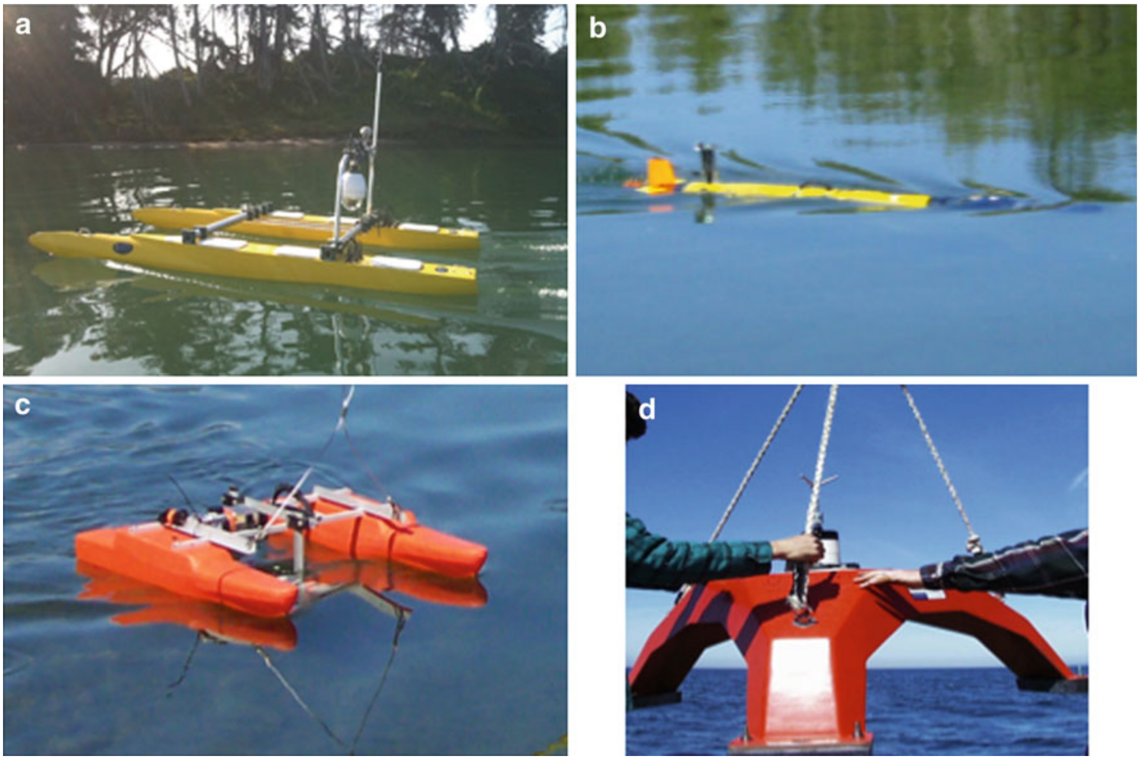

Fig. 1 Instrument platforms used to obtain velocity profile measurements: **a** SeaRobotics USV-2600. **b** YSI/Oceanserver EcoMapper Iver2 UUV. **c** Surface mini-catamaran with downward-looking ADCP. **d** Tri-pod used for bottom-mounted upward-looking ADCPs

2 Autonomous vehicles

2.1 Unmanned Surface Vehicle (USV)

The Sea Robotics USV-2600 (Fig. 1a), discussed herein, is a 1.9 × 1.25 m fiberglass twin-hull catamaran, which weighs about 360 lbs with all instrumentation included. It is powered by dual weedless propellers, located about 0.5 m below the water surface. The USV is designed to support multiple in-situ sensors that can be configured to meet the user's requirements for taking measurements in any type of environment. The USV supports a 1.2 MHz, 4-beam bottom-tracking RDInstruments (RDI) ADCP, a Differential Global Positioning System (DGPS) antenna, a single-beam echosounder, and heading, altitude, and several water quality sensors. It has an onboard data storage capacity of 3 GB and provides the user plenty of memory to complete a full day of data collection. Data can also be streamed real-time over the 2.4 GHz frequency band via radio antenna as long as line-of-site with the USV is achieved. The USV is powered by two Lithium Polymer battery packs capable of producing a top speed of 4.7 m/s. The USV can survey a given environment for up to 10 h while operating at 1.5 m/s and can last up to 1.5 h at 3 m/s.

The SeaRobotics USV-2600 has the unique capability to station-keep owing to its dual-propeller design. The station-keeping feature is the best method for collecting statistically reliable data as it removes the spatial sampling constraints, e.g. stationarity. The USV does not have an Inertial Measurement Unit (IMU); however, since USVs operate on the water surface, continuous DGPS allow for precise navigation and position recording, and vehicle motion is accounted for in the ADCP data processing associated with bottom-tracking. USVs tend to be larger than their UUV counterparts, requiring a wheeled-trailer for transport and deployment. The USV's increased size tends to provide an increase in payload, allowing for more battery capacity and increasing operational speed and duration. Making additions and modifications to USVs also tends to be easier for the end-user owing to the large deck space, which provides flexibility to adapt the USV for various environmental measurement needs.

2.2 Unmanned Underwater Vehicle (UUV)

The YSI/Oceanserver EcoMapper Iver2 UUV (Fig. 1b), discussed herein, measures 1.6 m long with a diameter of 0.15 m and weighs 45 lbs in air. The UUV can operate at depths down to 60 m using four independent control planes, and can travel at a speed of 0.5–2 m/s, with a maximum speed of 1 m/s on the surface. For navigation at the surface and to verify its position, the UUV uses GPS with WAAS corrections to provide positional accuracy better than 3 m. The UUV configuration includes a Sontek 10-Beam, bottom-tracking DVL (up- and down-looking configurations consisting of four velocity beams operating at 1.0 MHz and a vertical center beam operating at 0.5 MHz each), allowing for improved underwater navigation and water current profiling, a dual-frequency side-scan sonar for bottom imaging, and a full suite of water monitoring sensors that measure conductivity, temperature, depth, pH, dissolved oxygen, chlorophyll, blue-green algae, turbidity, and rhodamine. The UUV does not have an IMU; however, the vehicle motion is accounted for in the ADCP data processing associated with bottom-tracking. The UUV has an onboard data storage capacity of 10 GB and runs on rechargeable lithium-ion batteries, making it capable of up to 8 h of data collection at a speed of 1.3 m/s in a no flow environment.

UUVs are now stable and reliable platforms for conducting continuous surveys of the water column in environments with flows less than a few knots. Unlike USVs, UUVs are normally equipped with a single propeller, which limits the UUV's turning radius and its ability to station-keep. The YSI/Oceanserver EcoMapper Iver2 UUV does have the ability to remain quasi-stationary by using a "park" mode for a user-defined duration. The "park" mode is only functional at the surface and allows the UUV to station-keep at a specific point within a user-defined radius utilizing its GPS antenna with WAAS corrections. The UUV "park" mode is defined by an inner and outer park radius, with a minimum outer radius of 3 m. In a unidirectional current, the vehicle drives to the center of the inner park radius, then turns off the propeller and floats. When the vehicle floats downstream beyond the outer park radius, it drives back to the inner park radius, repeating this for the defined park duration. Field experience has shown that the "park" mode works best when the vehicle is traveling upstream and in moderate to fast flows and can hold position within a 10 m linear excursion. Although outside of the original intent of the park mode, we utilized this mode for obtaining a statistically confident velocity profile at a relatively stationary location.

There are several logistical problems with using the UUV in park mode because it must operate at the surface. Since the UUV is small and a majority of the body floats below the surface it can be difficult to see by other boat operators. For this reason, it is recommended that a support vessel be used to warn boat traffic about the UUV's location. A tethered surface float can be attached to the UUV to increase visibility, but this increases the drag on the UUV and decreases operational time. Also, the effect of short period wind waves may cause the UUV to pitch and roll significantly more while at the surface. Last, but most important, the probability of floating surface debris, such as grass and seaweed, getting wrapped around the propeller increases when the UUV operates at the surface. It is recommended that the UUV operate below the surface at >1 m/s where the vehicle is stable and less prone to propeller fouling and being hit by other boaters. However, caution is required when analyzing the fast-moving vessel ADCP data to ensure environmental flow characteristics are not changing over the spatial range covered during the averaging duration.

3 Experiments

The AVs equipped with ADCPs, as well as several other platforms with velocity profiling instruments, were deployed in various environments under differing flow conditions (Table 1) to evaluate the performance of the AVs and to determine the appropriate sampling techniques.

3.1 Kootenai River, ID, August 2010

ADCP velocity profiles were collected by the USV as part of a riverine field experiment conducted in August 2010, on the Kootenai River, ID, referred to as KR (Fig. 2a–c). The primary goal of the experiment was to accurately measure the 3D flow field in a natural river composed of varying depths and channel meanders. The backwater meandering reach of the KR (Fig. 2b), which was approximately 8 m deep, 200 m wide, and had flows of 0.4 m/s, was measured by the USV. The meandering reach was divided into 14 transects oriented normal to the river bank with variable streamwise spacing for enhanced resolution of the flow dynamics around the river bends. Each transect consisted of five locations spaced equally across the river, at which the USV would station-keep to within a few meters for approximately 10 min. The ADCP mounted on the USV sampled at 0.5 Hz and acquired velocities throughout the water column with a surface blanking distance of 0.35 m, a 0.25 m bin size, and 28 depth bins. Precise positioning and navigation to each transect and subsequent stationary profile location were achieved by the onboard DGPS. An additional onboard survey-grade DGPS was post-processed after the mission to improve the USV positions. It was found that the USV could maintain positioning to within 1 m. This high degree of positional accuracy is necessary for describing the complex flow structures that can occur across the width of a river. The efficiency of the USV to go to a specified location, station-keep, and then continue cannot be matched by single-propeller, human-controlled vessels, which generally have the additional requirement of anchoring.

In addition, self-contained, downward-looking 2 MHz Nortek Aquadopp ADCPs mounted on surface, non-motorized, mini-catamarans (Fig. 1c) were deployed in the braided reach of the KR (Fig. 2c), which was 3 m deep, 100 m wide, and had flows of 1.5 m/s. Three mini-catamaran-ADCP systems, equally spaced in the across-stream direction, were hand deployed from a boat in transects along the braided

Table 1 Experiment locations, conditions, instrument platform and settings, and conservative mean (mean plus one standard deviation) averaging window

Location	Flow conditions (m/s)	Depth (m)	Platform	Method	Velocity profiling instrument	Sampling rate (Hz)	Number of bins	Bin size (m)	Blanking distance (m)	Conservative mean T_* (min)
Kootenai River—meandering reach (August 2010)	0.40	8	USV	Station-keeping	RDI ADCP (1.2 MHz)	0.5	28	0.25	0.35	2.9
Kootenai River—braided reach (August 2010)	1.5	3	Surface mini-catamaran	fixed	Nortek Aquadopp (2 MHz)	1*	35	0.20	0.05	3.6
Elkhorn Slough (November 2010)	0.40–1.00	4	USV	Station-keeping	RDI ADCP (1.2 MHz)	0.5	40	0.25	0.35	2.8
Elkhorn Slough (August 2009)	0.40–1.00	5	Bottom tri-pod	Fixed	Nortek Aquadopp (2 MHz) and Nortek AWAC (1 MHz)	0.5	20	0.35	0.05	3.2–3.5
Bear Cut inlet, Miami, FL (January 2011)	>1.00	6	UUV	Park mode	Sontek ADCP (1.2 MHz)	1*	30	0.5	0.25	3.3

* denotes instruments with a sample rate of 1 Hz, which were averaged to a new 0.5 Hz sample rate

reach. At each transect the mini-catamarans were anchored to the bottom for 10 min durations to collect stationary ADCP measurements. The ADCPs on the mini-catamarans sampled at 1 Hz and had a surface blanking distance of 0.05 m, a 0.2 m bin size, with 35 depth bins.

3.2 Elkhorn Slough, CA, November 2010

A subsequent 6-hr USV mission was performed in November 2010, in Elkhorn Slough, Monterey Bay, CA, referred to as ES, which is a shallow, tidally-driven slough (Fig. 2d, e). ES is approximately 10 km long and consists of a main channel with a complex curving structure, mud flats, a salt marsh, and numerous small tidal channels [3]. The ADCP on the USV sampled at 0.5 Hz and measured velocities over the water column with a surface blanking distance of 0.35 m, a 0.25 m bin size, and 40 depth bins. The USV collected data over ebb and flood tidal conditions, station-keeping six times at the same point for 30 min at a time (Fig. 2e). The goal of this deployment was to capture the flow velocity while the USV was stationary in order to compare ADCP measurements in high discharge environments (ES) and low discharge environments (KR).

3.3 Elkhorn Slough, CA, August 2009

Additional velocity profiles obtained from bottom-mounted upward-looking sensors (Fig. 1d) deployed during a prior experiment that lasted 9 days in August 2009, in Elkhorn Slough, CA, are also used in this analysis to provide true stationary measurements for comparison with the AV's ADCP measurements. Three 2 MHz Nortek Aquadopp ADCPs and one 1 MHz Nortek Acoustic Wave and Current (AWAC) profiler were deployed and operated continuously with a sampling rate of 0.5 Hz to measure the tidal flow in the water column with a bottom blanking distance of 0.05 m, a 0.35 m bin size, and 20 depth bins. These stationary ADCP measurements were used to calculate averaging windows for flows ranging from 0.40 to 1 m/s for comparison with the AVs.

3.4 Bear Cut inlet, FL, January 2011

The UUV was utilized in January 2011, in Bear Cut inlet, Miami, FL, referred to as BC. BC is a naturally occurring inlet between two barrier islands, Virginia Key and Key Biscayne (Fig. 2f, g). This was a shallow water effort, with the goal of obtaining velocity profiles, bathymetry, and water quality observations in an environment experiencing flows greater

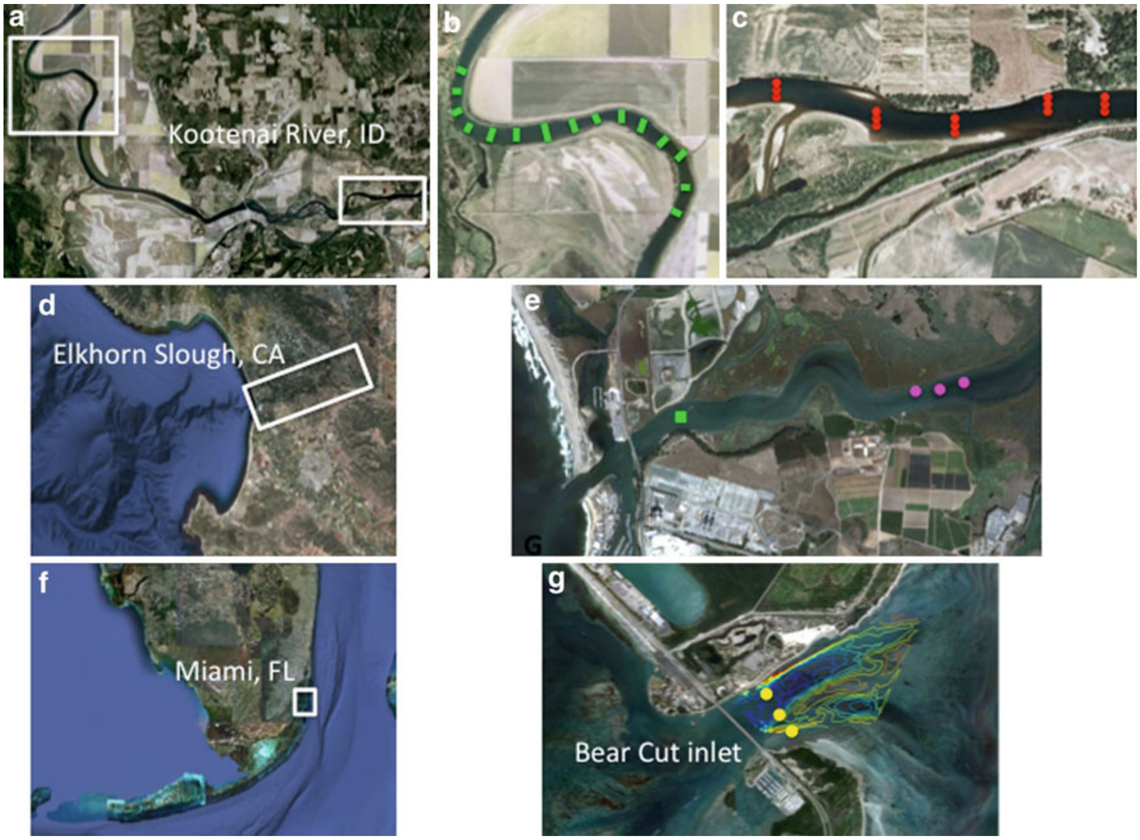

Fig. 2 Experiment locations: **a** Kootenai River, ID, and view of **b** the meandering reach and associated USV transects, and **c** the braided reach and mini-catamaran locations; **d** Monterey Bay, CA, and view of **e** Elkhorn Slough including the USV stationary point (*square*) and the stationary ADCP locations (*circles*); **f** Miami, FL, and view of **g** Bear Cut inlet and bathymetry obtained with the UUV and the UUV park locations

than 1 m/s. Previously, the UUV successfully executed missions in flow regimes less than 1 m/s. The UUV was used in "park" mode to obtain stationary velocity measurements, similar to the station-keeping USV missions, with the UUV facing upstream and propelling the vehicle as necessary to stay within the park radius for a specified amount of time. At BC, the UUV parked at three locations for approximately 5 min each, collecting ADCP velocity profiles. The ADCP sampled at 1 Hz and had a surface blanking distance of 0.25 m, a 0.5 m bin size, with 30 depth bins.

4 Analysis and results

Examples of noisy instantaneous velocity profiles measured by the station-keeping USV at KR and by the UUV in "park" mode at BC are shown in Fig. 3a, d. In order to reduce the statistical noise, time averaging is required. Profiles of velocity magnitude averaged over the duration of the stationary time interval (about 5 min) are shown in Fig. 3b, e. The minimum averaging time required to resolve the instrument and environmental noise is investigated further. By averaging measured velocity profiles over varying sampling times, a stable estimate of the mean is eventually reached (Fig. 3c, f). Previous work suggests sampling for about 7–11 min at a fixed location based on visual inspection of the mean velocity as a function of sampling time [17]. However, a quantifiable metric to determine the appropriate averaging time is desired.

Two statistical methods are used to determine the appropriate averaging window, T_*, such that a stable estimate of the mean flow is obtained: (1) a window-varying time average and (2) the Kalman Algorithm. These techniques are only used to determine T_* for describing the appropriate station-keeping time, and are not meant to be repeated in the field, owing to the need of a priori information. Both methods were applied to a 10-min time-series of the flow magnitude ($U = \sqrt{u^2 + v^2}$) and direction (θ) measured by the USV with a $dt = 2$ s in the KR at one depth. The window-varying time-averaging method computes the mean value at a given time step as the average of all of the data up to that time. This method is represented by the following equation:

$$U(n)_{\text{avg}} = \frac{1}{n} \sum_{n=1}^{\text{population}} U(1 \rightarrow n), \tag{2}$$

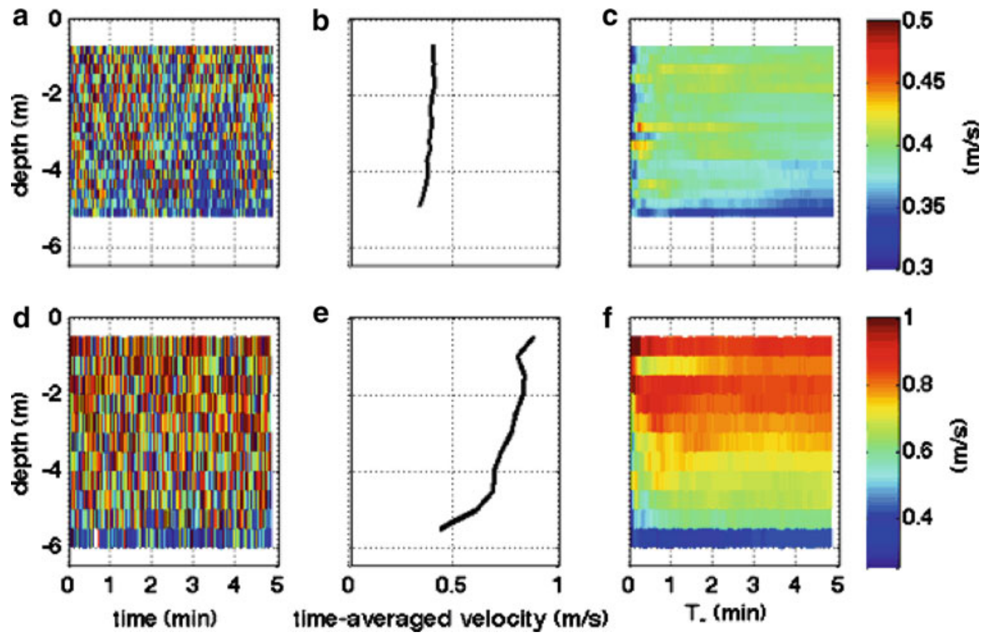

Fig. 3 ADCP data collected by the station-keeping USV in KR (*top row*) and the UUV in "park" mode at BC (*bottom row*): **a, d** raw flow magnitude as a function of time and depth, **b, e** time-averaged vertical flow magnitude profiles, and **c, f** window-varying time averaged flow magnitude as a function of averaging window and depth. *Colorbars* represent flow velocity magnitude

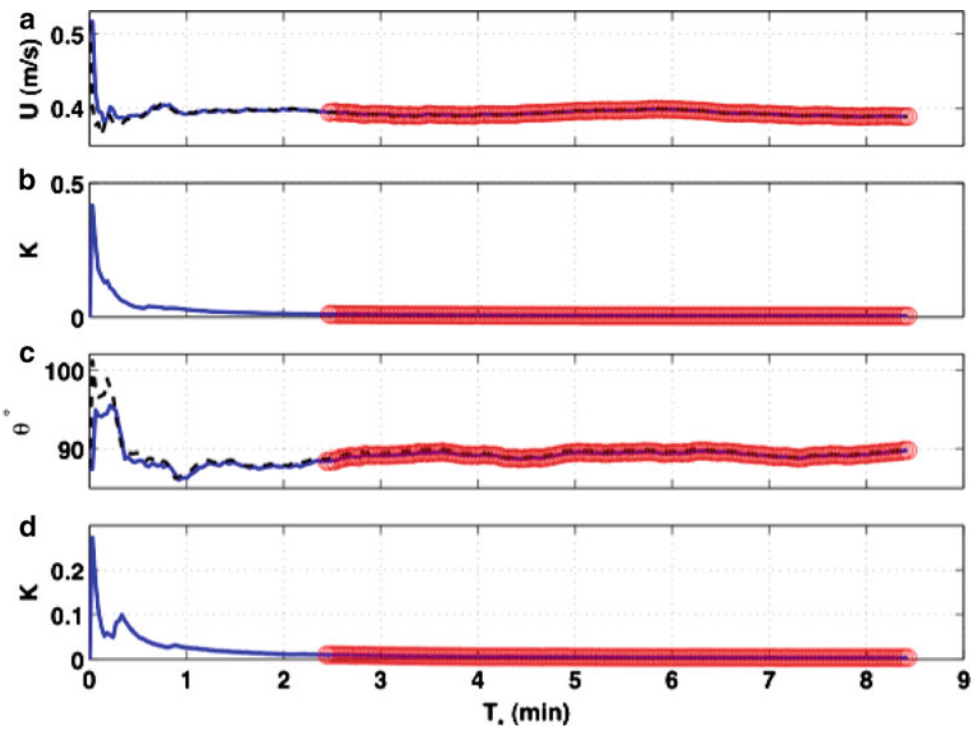

Fig. 4 Values of **a** flow velocity magnitude estimated by the window-varying time average method (*dahsed*) and by KA (*solid*), **b** velocity magnitude Kalman gain, K, **c** flow direction estimated by the window-varying time average method (*dashed*) and by KA (*solid*), and **d** direction Kalman gain, K, as a function of averaging window, T_*, for one ADCP bin from the station-keeping USV in KR. The *circles* indicate when $K < 0.01$ and the estimate of the mean is considered stable

where U is the flow magnitude and n is the number of observations in the averaging window, starting at $n = 1$, and increasing to the size of the population. This equation can be re-written such that once U_{avg} is calculated for a given averaging window, previous data do not need to be stored, and a new observation simply updates U_{avg} by

$$U\ (n+1)_{\text{avg}} = \frac{1}{n+1} U\ (n+1)_{\text{observation}} + \frac{n}{n+1} U\ (n)_{\text{avg}}\,, \qquad (3)$$

where $U(n)_{\text{avg}}$ is the mean from the previous averaging window and $U(n+1)_{\text{observation}}$ is the new observation at $n+1$. Equation 3 shows that as the number of observations increases, the impact of a new observation on the mean decreases by $1/(n+1)$, which is referred to as the averaging gain. As the averaging window increases, the velocities asymptote to a constant value, which is the mean flow. The estimate of the mean U and θ becomes qualitatively stable for averaging windows greater than 60 s, (Fig. 4a, c). However, even though the mean appears relatively constant after 60 s, small variations still exist, which can result in errors when describing the velocity profile.

A statistical metric for determining when the time-averaged signal asymptotes (an appropriate T_*) is required such that the observations provide a stable estimate of the mean and additional observations provide minimal new information. The Kalman Algorithm is a statistical method for repeatedly updating the estimate of the mean of an evolving system from a sequence of "noisy" measurements by processing a succession of additional measurements [14]. The Kalman Algorithm (KA) is defined as

$$U_{N+1} = K \times (U_{\text{observation}} - U_N) + U_N, \tag{4}$$

where U_N is the previous estimate of U, K is the Kalman gain, $U_{\text{observation}}$ is the new observed value at N+1, and N is equal to the number of independent observations (degrees of freedom) at that step. K is defined as

$$K = \frac{\sigma_N^2/N}{\sigma_N^2/N + \sigma_{\text{population}}^2} = \frac{1}{1+N} \text{ as } N \to \text{population}, \tag{5}$$

where σ_N^2 is the variance at N, and $\sigma_{\text{population}}^2$ is the system variance, which is assumed here to be equal to the variance for the total duration of 10 min. As N increases to the size of the population, $\sigma_N^2 = \sigma_{\text{population}}^2$ and $K = \frac{1}{(1+N)}$. When K is small, the adjustment to the prediction is minimally affected. For averaging windows less than 60 s, K has large initial fluctuations, but then exponentially decays for a larger sample size, and is similar for flow magnitude and direction (Fig. 4b, d).

A T_* was chosen when a sufficient number of independent observations were collected to obtain a $K = 0.01$, as it provides a conservative threshold for describing the mean flow magnitude and direction. This states that any new observation only improves the estimate of the mean by 1% of the new measurement difference ($U_{\text{observation}} - U_N$). As K continues to decrease, new observations provide minimal new information to the system, even if the new observation is large. A larger K threshold can be used, resulting in a decrease in T_*, but with reduced confidence in the mean velocity estimate. The important aspect of this approach is that a consistent K is used to evaluate ADCP response. Any reasonable K value would provide satisfactory results, but we focus on T_* determined when $K = 0.01$, which suggests that the estimate at this time is stable.

Results using the window-varying time average method (Eq. 2) and the KA method (Eq. 4) are comparable (Fig. 4a, c). The largest differences between the two methods occur for $T_* < 60$ s. As time increases, both methods are essentially the same (Eqs. 3, 4). In general, KA estimates the asymptotic mean faster than just averaging. This is because the estimate of the mean by KA (Eq. 4) uses an amount proportional to the difference between the new observation and the previous estimate of the mean ($U_{\text{observation}} - U_N$), whereas using the averaging method (Eq. 3) uses the entire value of the new observation ($U_{\text{observation}}$), which includes more noise and has a greater impact when there are a small number of observations. Another key difference between the two methods is the KA retains the system variability (Eq. 5) and is related to the number of *independent observations*, N, while the window-varying time average (Eq. 3) depends solely on the number of observations, n (regardless of independence). If T_* was estimated when the averaging gain equaled 0.01, then all of the times would be the same, as it is strictly dependent on the number of observations. K is dependent upon the population variance and the instantaneous variance, which will vary based on ADCP manufacturer, settings, and environmental conditions. Differing system variance for varying instrument ADCP manufacturers is shown in Fig. 5. Regardless of manufacturer the variances increase with increasing flow magnitude. The KA method is used for all subsequent analysis because it provides a quantifiable metric for determining the appropriate T_*, and it accounts for the variability of the system in estimating the mean.

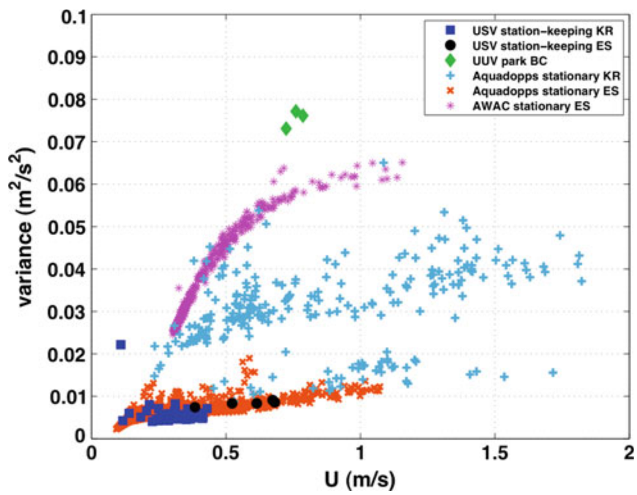

Fig. 5 Depth-averaged flow velocity magnitude variance versus depth-averaged mean flow velocity magnitude measured by ADCPs mounted on various stationary platforms in differing environments

The criterion for the decorrelation time is when the autocorrelation, $R(\tau)$, has decreased from the initial value, $R(\tau = 0\text{ s})$, by a factor of 1/e. The decorrelation time of U measured by both the USV in KR, with $dt = 2$ s, and an Aquadopp in KR, with $dt = 1$ s, occurs in one dt for each instrument (Fig. 6) and is consistent with Muste et al. [17]. For comparison, measurements taken by an Acoustic Doppler Velocimeter (ADV), deployed simultaneously in the braided reach of KR, were examined because ADVs can sample faster ($dt = 1/32$ s). The U_{ADV} signal was low-pass (LP) filtered with a frequency cut-off of 1 Hz, which was the onset of the noise

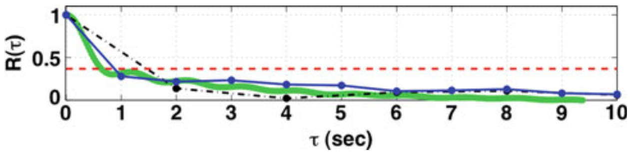

Fig. 6 Autocorrelation functions as a function of time lag, τ, for U measured by: the station-keeping USV in KR with $dt = 2$ s (*dash-dot line*), an Aquadopp in KR with $dt = 1$ s (*solid line*), and the ADV in KR with $dt = 1/32$ s (*thick sold line*), where the *dashed line* represents the decorrelation criteria (1/e)

floor. $U_{\mathrm{ADV,LP}}$ decorrelates in less than 1 s, suggesting that the environmental fluctuations are temporally short (Fig. 6). ADCPs intrinsically sample at a faster rate (<1 s), but record an average of these faster observations at a slower rate (>1 s), which is longer than the environmental decorrelation time as found by the ADV. Therefore, a decorrelation time is limited by the ADCP's slower sample "recorded" rate (>1 s). ADCPs with bottom-tracking have an even slower sample rate (>2 s) because the ADCP is sampling both water profile and bottom track estimates independently. The Aquadopps and AWAC do not have bottom-track capabilities, allowing for a faster "recorded" sample rate. The focus of the manuscript is for ADCPs with bottom-tracking, as these are the systems commonly found on AVs. Therefore, the resampling of all instruments to a $dt = 2$ s eliminates the influence of dt when evaluating the effects of depth, environmental conditions, platform, and instrument manufacturer on T_* and provides a conservative estimate for the number of independent observations. Note that the relative flow magnitude and direction of the environment was obtained in approximately 60 s, when $dt = 2$ s (Fig. 4a, c). This corresponds to 30 observations, which is considered a large sample size and is statistically a sufficient amount to accurately describe the mean [4]. However, Muste et al. [17] showed that the time requirement to resolve the velocity mean exceeds this statistical parameterization. Measurements acquired in differing environments with several instruments and platforms are evaluated to determine a statistically accurate averaging time.

The relationship between T_* computed for the flow magnitude (U) and for the flow direction (θ) using depth-averaged measurements from the station-keeping USV in KR is poor ($R^2 = 0.18$), suggesting there is no dependent relationship (Fig. 7). However, both measures indicate T_* of approximately 2.5 min. In other words, the T_* for the cross- and along-channel velocities are independent, but similar.

Velocity measurements from all of the experiments were analyzed to determine how T_* varies by depth, environment, platform, and instrument manufacturer. The mean T_* values,as a function of depth, calculated from stationary measurements by the differing platforms and ADCPs during each experiment are shown in Fig. 8. Based on a 95% confidence level, T_* is only statistically uniform over the vertical for

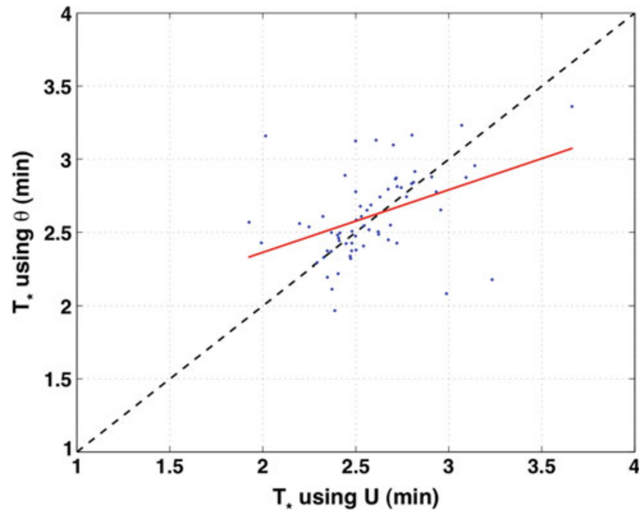

Fig. 7 Correlation between T_* calculated using flow velocity magnitude (U) and T_* calculated using flow direction (θ). The *dashed line* represents an idealized linear regression line and the *solid line* represents the actual liner regression line for the comparison ($R^2 = 0.18$, $m = 0.43$)

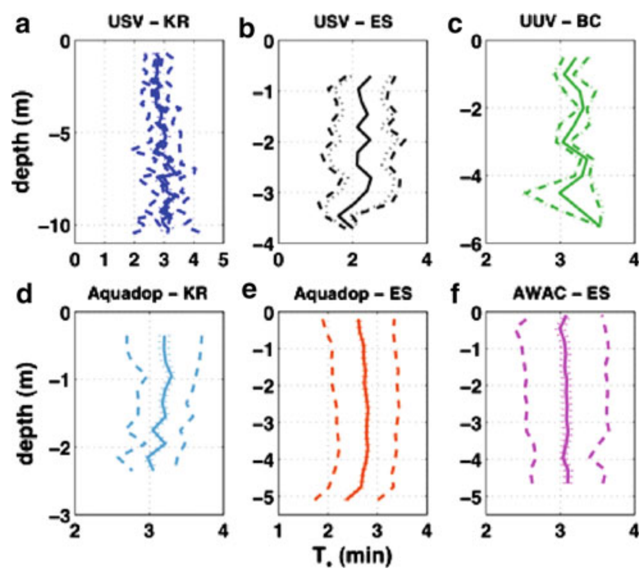

Fig. 8 Averaging window, T_*, as a function of depth, determined for **a** the station-keeping USV at KR, **b** the station-keeping USV at ES, **c** the UUV in "park" mode at BC, **d** stationary downward-looking Aquadopps at KR, and for the fixed bottom-mounted **e** Aquadopps and **f** AWAC in ES. Note that all ADCPs were stationary. *Solid lines* depict the mean averaging window, *dashed lines* depict one standard deviation, and *dotted lines* depict the 95% confidence level

the USV measurements in ES and for the mid-water column measurements by the Aquadopps and AWAC in ES. However, the T_* values are relatively the same throughout the water column for all of the measurements, with the exception of the UUV, regardless of the platform, ADCP manufacturer, and environmental conditions. Only three vertical profiles were measured with the UUV; therefore, there were

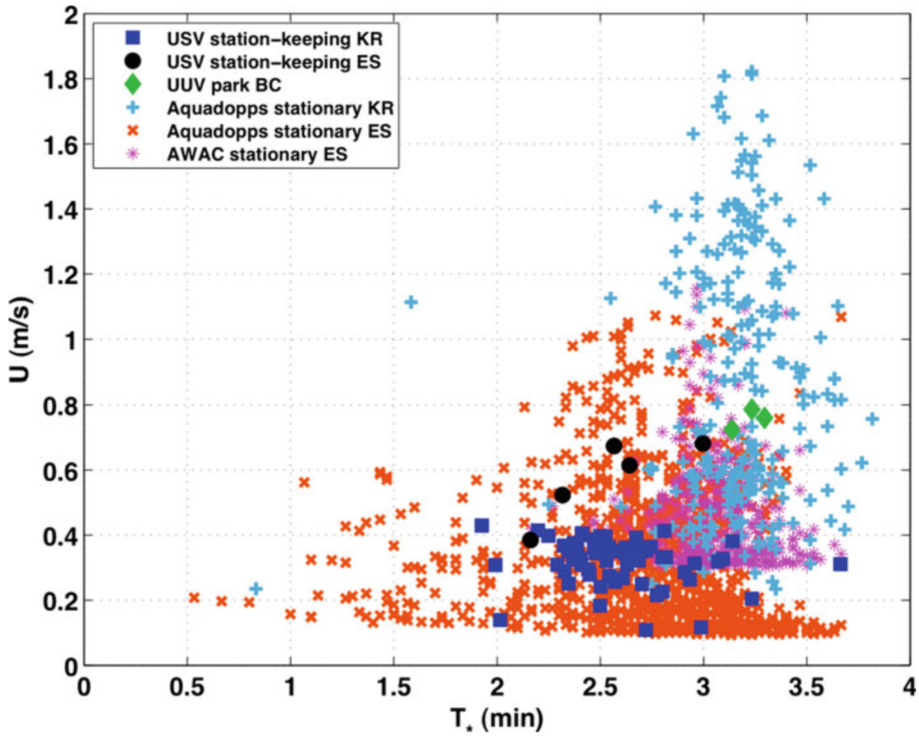

Fig. 9 Depth-averaged flow velocity magnitude versus depth-averaged averaging window, T_*, measured by ADCPs mounted on various stationary platforms in differing environments

not enough data to conclude that the mean vertical profile was statistically uniform.

Examining the results from the AVs in differing environments suggests T_* is similar regardless of flow conditions for each platform, with relatively small differences in T_* between AVs. In a low-flow environment (0.4 m/s) in the meandering reach of the KR, T_* for the station-keeping USV varied throughout the river resulting in a mean T_* of approximately 2.6 min (Fig. 8a). The standard deviation is 0.3 min resulting in a conservative T_* limit of 2.9 min. Comparatively, in a higher flow environment (0.4–1 m/s) in ES, the mean and standard deviation for T_* for the station-keeping USV was similar at 2.5 and 0.3 min, respectively (Fig. 8b). The results are the same for the USV in the varying flow conditions. Owing to these values, it is recommended that the USV station-keep at the same location for a minimum of 3–4 min to ensure that a stable estimate of the mean is obtained. In the fastest flows (>1 m/s) in BC, the mean and standard deviation of T_* measured by the stationary UUV (Fig. 8c) were similar to the station-keeping USV results, at 3.2 and 0.1 min, respectively.

Although the AVs were considered stationary when performing station-keeping and "park" missions, there was still some vehicle movement. The speed of the USV while station-keeping was negligible (<0.01 m/s) and the UUV moved an average of 0.17 m/s while in park mode. The speed of the AVs while maintaining a stationary position was determined based on bottom-track velocities, which have less than a 6% error compared with kinematic GPS measurements [8]. To further evaluate potential errors that developed because of the moving platform, T_* for the bottom-mounted stationary ADCPs deployed in ES were estimated (Fig. 8e, f). Note that these stationary ADCP measurements were not collected at the same time as the USV mission in ES. The conservative T_* (mean plus one standard deviation) for the bottom-mounted Aquadopps and AWAC were 3.2 and 3.5 min, respectively. These T_* values are comparable to the station-keeping USV, even though the ADCP manufacturers are different. These results indicate that the station-keeping AVs are stationary enough to obtain stable estimates of the mean flow in similar time frames as true stationary measurements. Additionally, the downward-looking Aquadopps mounted on stationary surface mini-catamarans in KR (Fig. 8d) resulted in a conservative mean T_* of 3.6 min, which is in the range of the other measurements.

The depth-averaged T_* for the various platforms in different flow environments are shown in Fig. 9. The mean T_* was found to be about 3 min with a maximum T_* of less than 4 min, with a weak relationship with the depth-averaged velocity. T_* for the USV measurements varied by about 1 min over a relatively small velocity range, whereas T_* for the Aquadopp in KR was constantly about 3.2 min for a larger velocity range (1.5 m/s). However, the Aquadopps deployed in ES had T_* values ranging from 0.5 to 3.5 min for a similar large velocity range. Therefore, there is no significant dependence of T_* on flow condition, platform, or ADCP manufacturer, and a conservative value of 4 min will provide a stable estimate in any scenario.

5 Summary

As with any observational endeavor, an acceptable prior level of statistical confidence is required. The effectiveness of using ADCPs on AVs at fixed locations to obtain accurate measurements of the mean flow conditions in various rivers and estuaries has been investigated. Using the Kalman Algorithm with a Kalman gain of $K = 0.01$ provided a useful method for estimating a statistically relevant T_* for obtaining high-quality ADCP horizontal velocity profiles. The mean T_* for various ADCPs and platforms was found to be 3 min with a maximum T_* of less than 4 min, with minimal dependence upon instrument type and the environmental conditions. Surprising to the authors, all ADCPs and their platforms responded similarly. The conservative T_* is two times smaller than those found in previous studies examining moving and fixed vessel ADCP measurements [17,19]. The instrument sampling rate, dt, can influence T_*, with T_* decreasing with decreasing dt. T_* is not dependent on depth or flow velocity, and there is no correlation ($R^2 = 0.18$) between using flow velocity magnitude and direction. A conservative time of 4 min of observations at a specific point should be acquired to obtain an accurate estimate of the mean velocity profile. If ADCP observations are collected with a moving vessel, the distance travelled in 4 min should be spatially stationary. The statistical techniques implemented in this work provided a robust means of determining the 4-min averaging time window for these platforms, ADCPs, and riverine/estuarine environments. The techniques do not need to be repeated, unless these conditions significantly change.

The UUV was able to perform surface station-keeping ("parks"); however, the UUV works best when operating below the surface and at a speed greater than 1 m/s. At these speeds, the UUV will have traveled approximately 240 m in the necessary averaging window. If flow along this transect can be considered temporally and spatially stationary (homogeneous), an accurate description of the profile can still be resolved.

The USV can precisely execute repeated station-keeping positions in varying environments. An example of the USV's spatial velocity measurement capability is shown in Fig. 10. In planning the mission, a station-keeping time of 10 min was used to resolve the mean velocity profiles [17]. The USV successfully and efficiently mapped the velocity structure (Fig. 10) in the meandering reach of the KR in 2 days. With the new knowledge that a conservative T_* of 4 min is necessary, the number of observational locations could have doubled, resulting in an even better description of the river flow field. The capabilities of the AVs to map the 3D flow conditions of an environment accurately and efficiently, in time and space, far exceed the capabilities of human-controlled vessels. AVs provide scientists an indispensable tool to effectively study various flow environments.

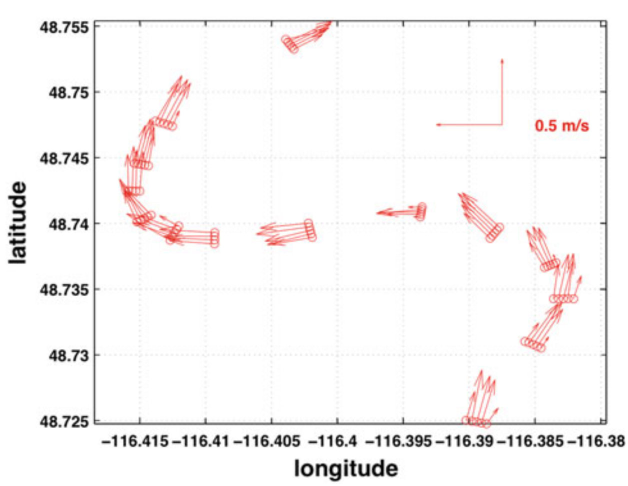

Fig. 10 Spatial map of the velocity field in the meandering reach of the KR measured by the station-keeping USV

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